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Calculation methods for single-sided natural ventilation - simplified or detailed?

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Abstract

A great energy saving potential lies within increased use of natural ventilation, not only during summer and midseason periods, where it is mainly used today, but also during winter periods, where the outdoor air holds a great cooling potential for ventilative cooling if draft problems can be handled.

This paper presents a newly developed simplified calculation method for single-sided natural ventilation, which is proposed for the revised standard FprEN 16798-7 (earlier EN 15242:2007) for design of ventilative cooling. The aim for predicting ventilative cooling is to find the most suitable simple method that will in average perform well, while reducing the risk of overestimating airflows in individual cases with different temperature difference, wind direction and wind velocity. Therefore, the results from the new and simplified calculation method will underestimate the measured (real) airflow.

The predicted airflow rate from the new and three existing design expressions are compared to full-scale wind tunnel measurements. The new proposed calculation method for single-sided ventilation shows results, limiting the overestimation of air flow rates at especially low driving pressures, while maintaining an acceptable correlation with measurements on average and the authors consider the simplified calculation method well suited for the use in standards such as FprEN 16798-7 for the ventilative cooling effects from single-sided natural ventilation

The comparison of different design expressions reveals strengths and weaknesses based on the aim of the calculation. A guidance on when to use which level of details in the calculations are given.

Keywords - Single-sided ventilation; natural ventilation; calculation method; ventilative cooling

1. Introduction

As buildings become more and more insulated and airtight according to the tightening of national building regulations, the cooling demands increases and are for some buildings in colder climates not only found during summer and midseason periods but also during winter periods. A great energy saving potential lies within increased use of natural ventilation for handling the increasing cooling demands. The outdoor air during winter holds a great cooling potential if draft problems can be handled, and used in hybrid solutions, increased use of ventilative cooling also during winter periods, can be the solution that leads to large energy savings in buildings.

Implementing natural ventilation in building design might seem as uncertain due to the dependence on wind speeds and temperature differences across the window opening. But the potential for energy savings is too big to ignore this type of “free cooling” and the prediction of airflows can be done at different levels of detail, with different levels of certainty, and thereby also by different levels of time consumption for the calculations. Choosing between the different design expressions depends on where in the design process the prediction is done. At an early stage the opening areas for windows/vents, the orientation and the shape of the building might still be uncertain. For this purpose a fast and simple model is needed for prediction of the expected airflows caused by the natural ventilation. At a later stage, with more fixed parameters, a more detailed calculation can be made.

Another important issue when choosing the design expression is the purpose of the calculation. For general use of natural ventilation the predictions must be reasonably correct with a low tolerance of under estimations due to health and comfort. For ventilative cooling, the predictions must in average perform well, while reducing the risk of overestimating air flows in individual cases, and thereby overheating of the room. The implementation in a standard of a design method which frequently overestimates air flow rates would jeopardize the implementation of ventilative cooling. Indeed, if expected air flow rates are frequently not met, this could lead to frequent over-heating in a building, or buildings in which ventilative cooling never meet expectations. This would bring discredit on ventilative cooling techniques. On the opposite, using methods that remain on the safe-side leads to efficient installation and thereby promotion of ventilative cooling.

Natural ventilation can be designed as either single-sided ventilation (openings only on one side of the building) or cross ventilation (openings on two sides). This paper will consider the solutions developed for single-sided ventilation, where the airflows, besides temperature difference and wind, also depend on the turbulent flow caused by e.g. wind gusts near the opening. Three older design expressions for single-sided natural ventilation were developed by De Gids & Phaff (1982) [1], Warrens & Parkins (1985) [2] and Larsen (2006) [3], [4], all with different levels of details needed for the calculations. For the purpose of estimating the effect of ventilative cooling, a new calculation method developed as a modified version of De Gids & Phaff is

presented. This calculation method is proposed for the revised standard FprEN 16798-7 (earlier EN 15242:2007 [5]).

Knowing that a simplified method for ventilative cooling may underestimate the airflows, this paper compares the simplified and detailed methods by looking at the pros and cons; so where we miss out and where we gain from using simplified calculation methods for future standards and regulations and where in the design process we can skip the detailed calculations for a quick result and get on with the building design.

2. Methods

An evaluation of existing single-sided ventilation design expressions are made by parameter variations, comparison to wind-tunnel experiments and full-scale outdoor measurements, where the latter is not included in this paper. The evaluation is based on design expressions by De Gids & Phaff, Warrens & Parkins and Larsen, which are compared to a new simplified calculation method proposed for the upcoming EPBD standard FprEN 16798-7. The new simplified design expression is developed from a moderation of De Gids & Phaff to improve the calculation output according to the planned use in future standards and regulations for prediction of ventilative cooling, by in average performing well, while reducing the risk of overestimating air flows in individual cases.

2.1 Existing design expressions for single-sided ventilation

The airflow for single-sided natural ventilation depends on the wind velocity, temperature difference, wind direction and turbulence near the opening [1], [2], [4], [6]. Some sources only consider a single contribution and some combine the contributions. Warren & Parkins [2] split the contributions into two parts. The wind driven ventilation is found from (1) and (2), where the only difference is whether the known wind speed is the local or the reference wind speed. The airflow driven by buoyancy in a single opening is calculated by (3) [2].

$$\text{Wind:} \quad Q_v = 0.1 \cdot A \cdot U_L \quad (1)$$

$$\text{Wind:} \quad Q_v = 0.025 \cdot A \cdot U_R \quad (2)$$

$$\text{Buoyancy:} \quad Q_v = \frac{1}{3} \cdot C_D \cdot A \cdot \sqrt{\frac{(T_i - T_e) \cdot g \cdot (H_t - H_b)}{\bar{T}}} \quad (3)$$

Where, Q_v is the volume flow rate [m^3/s], A is the area of the opening [m^2], U_L is the local air speed at the surface of the building near the window [m/s], U_R is the reference wind speed [m/s], C_D is the discharge coefficient (takes the shape of the opening into consideration) [-], T_i is the internal temperature [K], T_e is the external temperature [K], \bar{T} is the average temperature [K], g is the gravitational acceleration [m/s^2], H_t is the height, top of the opening [m] and H_b is the height, bottom of the opening [m].

The combined effect of wind speed, buoyancy and turbulence was handled by the expression developed by De Gids & Phaff in 1982 [1]. This expression is still used today for “prediction of air flows due to windows opening” in the European standard EN 15242:2007 [5]. The expression is found in (4), [5]

$$\text{Wind, buoyancy, turbulence: } U_m = C_t + C_w \cdot U_{10}^2 + C_{st} \cdot H_{\text{window}} \cdot \text{abs}(\theta_i - \theta_e) \quad (4)$$

Where, U_m is mean air velocity in opening [m/s], C_t is the turbulence constant (=0.01), C_w is the dimensionless coefficient depending on the wind effect (=0.001), U_{10} is the mean wind speed in H=10 m [m/s], C_{st} is the buoyancy constant (0.0035), H_{window} is the height of the opening [m] and $(\theta_i - \theta_e)$ is temperature difference across the opening [K].

The volume flow rate can be found from (5), [5].

$$q_v = 3.6 \cdot 500 \cdot A_{ow} \cdot U_m^{0.5} \quad (5)$$

Where q_v is the airflow through the window [m³/h] and A_{ow} is the window opening area [m²]

The influence of wind direction on single-sided ventilation is included in the design expression together with wind speed, buoyancy and turbulence from Larsen in 2006. This expression is seen in (6).

$$Q_v = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot |C_p| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot H + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}} \quad (6)$$

The wind direction is included in expression (6) by the use of the pressure coefficient C_p , which depends on the wind direction and by the function $f(\beta)$, which includes the effect of local velocities near the opening. The fluctuations are defined by the pressure difference across the opening included in $\Delta C_{p,opening}$. Besides this three empirical coefficients found by experimental work, C_1 , C_2 and C_3 are used.

2.2 Development of simplified design expression for ventilative cooling

In 2015 a new and modified version of the original De Gids & Phaff expression was developed for the purpose of promoting ventilative cooling in the upcoming version of the revised standard EN 15242:2007 (now called FprEN 16798-7). The modified expression was based on the experiences and problems found for the prediction of single-sided natural ventilation with a combination of thermal buoyancy and wind. The experiences were:

- 1.) Earlier experiments [4] had shown an overestimation of air flow rates with the original De Gids & Phaff expression at low wind speeds and at no or very low temperature difference, which is a problem when the aim for ventilative cooling is to predict air flow rates through windows generally on the safe side and thereby with a need for underestimation (see also Figure 3a).
- 2.) Warren & Parkins described a problem with handling the combinations of wind and buoyancy effects in natural ventilation in some of their early work from 1977. They concluded that a difference between the wind dominated and temperature dominated cases exist and recommended to handle the combination of wind and buoyancy by calculating the effect from each parameter separately and then use the largest of them. Also Larsen and Heiselberg [3], [7] concluded that clearly wind dominated and temperature dominated cases were found from the measurement of flow patterns in the opening based on the levels of wind velocity and temperature difference in each specific case.

From the evaluation of the overestimation it was found that there always would be positive air flow contribution at low wind speeds and at no or very low temperature difference due to the fixed wind turbulence coefficient, C_t (see (4)). As a consequence of this, C_t was removed in the modified expression. Another modification of the original De Gids & Phaff expression was to split the modified calculation method into two separate contributions from wind and buoyancy respectively. For the modified De Gids & Phaff the highest value from the two contributions are used for calculation of the design air flow rate.

$$q_{V,arg} = 3600 \times \frac{\rho_{a,ref}}{\rho_{a,e}} \cdot \frac{A_{w,tot}}{2} \cdot \max \left(C_{wind} \cdot u_{10,site}^2 ; C_{st} \cdot h_{w,st} \cdot abs(T_z - T_e) \right)^{0,5} \quad (7)$$

Where $q_{V,arg}$ is the airflow through the window [m^3/h], $\rho_{a,ref}$ and $\rho_{a,e}$ are the reference and external air densities [kg/m^3], $A_{w,tot}$ is the total window opening area [m^2], C_{wind} is wind speed coefficient [-], $h_{w,st}$ is the useful stack effect height for airing [m], $T_z - T_e$ is the temperature difference between the ventilation zone and outdoor air [K].

2.3 Measurements in wind tunnel

In order to evaluate the new and modified De Gids & Phaff design expression (7), the calculated results were compared to wind tunnel measurements carried out on a full scale building (5.56 x 5.56 x 3 m) at the Japanese Building Research institute (BRI). The opening was 0.86 x 1.4 m (w x h) and positioned 0.54 m away from the right edge of the building. The internal room height was 2.4 m and the thickness of the walls was 0.1 m. The room volume was 68.95 m^3 .

The wind velocity in the wind tunnel was varied between 1, 3 and 5 m/s. The temperature difference across the opening was varied between 0, 5 and 10°C. During the experiments the model was rotated between 0° and 345° with either a 15° or a 30° increase to get measurements for different angles of the wind. The air change rate was measured for 159 different cases using the tracer gas decay method, [4]. The results from the measurements are shown in Figure 1 and Figure 2. From the Figures, the wind dominated and temperature dominated cases are clearly identified. At very low wind velocities, the effect from increased temperature difference is very significant (Figure 1a) and in the case without temperature difference, the effect of increased wind velocity is easy to identify (Figure 2a). The effect for other combinations with higher wind velocities/temperature differences get more blurred and becomes only significant for specific angles of the wind. So for leeward side (angles between 90° and 270°), the temperature difference stays dominant also for $U=3\text{ m/s}$ (Figure 1b) and for windward side the wind velocity stays the dominant parameter also for a temperature difference of 5°C (Figure 2b).

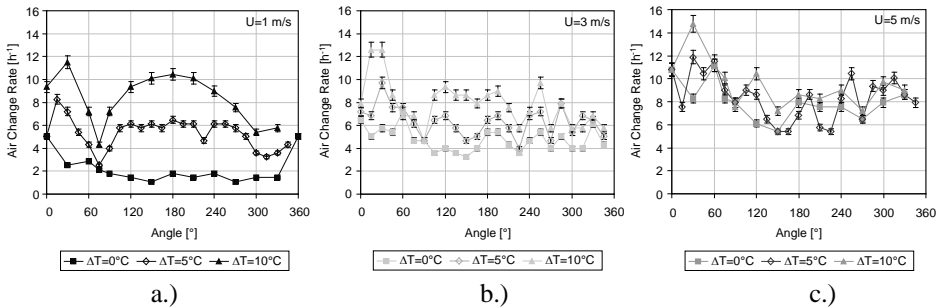


Figure 1. Effect on the air-change rate from changing the temperature difference at different incidence angles and wind velocities. [3]

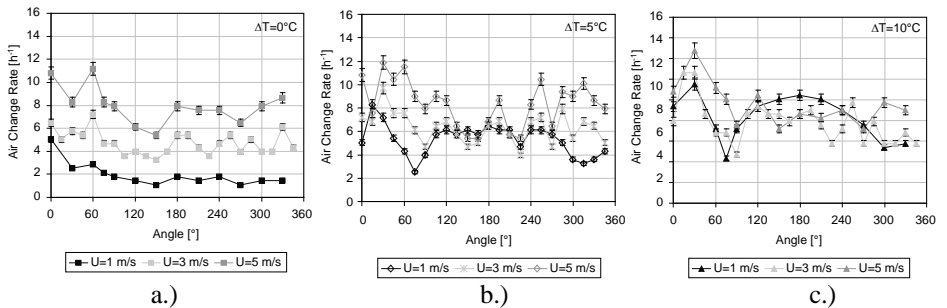


Figure 2. Effect on the air-change rate from changing the wind speed at different incidence angles and temperature differences. [3]

3. Results

The wind-tunnel measurements described in section 2 are in this section used for comparison with the different design expressions for design of single-sided natural ventilation. The situation with low driving forces was described as the most critical situation for the original design expression from De Gids & Phaff (4). An example of this situation is shown in Figure 3a with $\Delta T = 0^\circ\text{C}$ and $U = 1\text{m/s}$. Here it is seen that the modified De Gids & Phaff expression (7) underestimates the measured values for this case, which also was the purpose for the planned use with ventilative cooling in the upcoming European standard. The underestimation results in an average deviation between measured and calculated values for all angles of 41%. The original De Gids & Phaff for this case showed an overestimation of 95%. The design expression developed by Larsen (6), which also included the wind direction, shows an average underestimation of 29%.

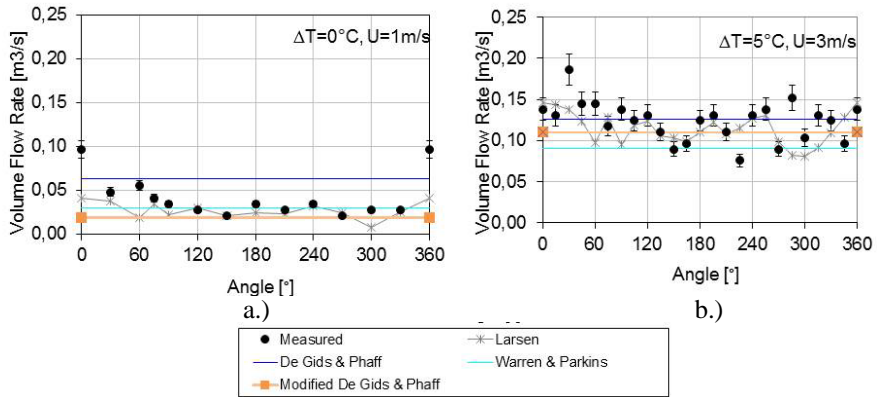


Figure 3. Comparison of wind-tunnel measurements and calculated air flow rates

The measurements used to illustrate the situation where the driving forces starts to have equal sizes is shown in Figure 3b. Here the modified De Gids & Phaff calculation method still results in lower air flows than the original De Gids & Phaff. The average underestimation found from the modified expression is for this case 21% whereas the original expression with combined contributions from wind and temperature difference overestimates with 6%. For this case Larsen overestimates with an average of 3%.

In Figure 4 comparisons between the calculated and measured values are made for the different design expressions presented in section 2. Overestimated values are above the black line.

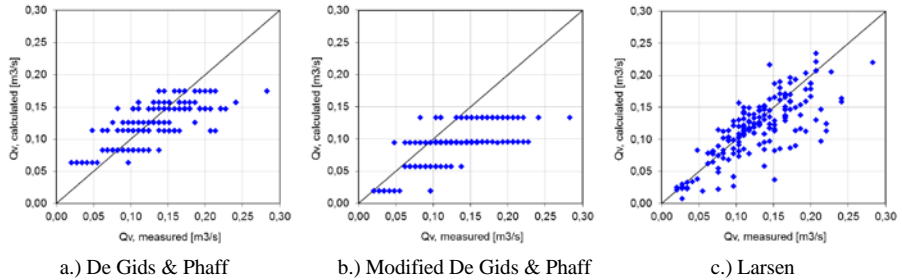


Figure 4. Comparison between measured and calculated values for the mentioned design expressions.

Figure 4b shows that the results for the modified De Gids & Phaff expression underestimates the air flow rate for the majority of the results. This was exactly the aim for the modified design expression, which was developed for the new standard FprEN 16798-7.

The deviations are calculated as:

$$\text{Deviation} = (\text{calculated} - \text{measured}) / \text{measured} * 100\% \quad (8)$$

The calculated result for the three design expressions from Figure 4 are found in Table 1. The average deviation is calculated as seen in (8) and is included to show whether the design expressions are over- or underestimating the airflow. The absolute deviation is calculated as the average value of the absolute value of the deviations to show the accuracy of the design expression.

Table 1. Calculated deviations between measured values from wind tunnel experiments performed by Larsen and calculated air flow rates.

Measurements		De Gids & Phaff		Mod. De Gids & Phaff		Larsen	
ΔT [°C]	U [m/s]	Average deviation	Absolute deviation	Average deviation	Absolute deviation	Average deviation	Absolute deviation
0	1	95%	101%	-41%	41%	-29%	35%
0	3	-5%	17%	-34%	34%	-18%	32%
0	5	-24%	25%	-36%	36%	-19%	33%
5	1	19%	25%	-2%	23%	14%	21%
5	3	6%	16%	-21%	24%	3%	15%
5	5	-4%	22%	-38%	38%	0%	20%
10	1	1%	25%	-9%	26%	2%	20%
10	3	7%	18%	-24%	18%	6%	18%
10	5	-1%	15%	-24%	24%	2%	13%
Average		11%	29%	-16%	29%	-4%	23%

The modified De Gids & Phaff expression in general underestimates the airflow. The largest deviations are found for all cases with $\Delta T=0^\circ\text{C}$. Higher accuracy is obtained for cases with combined driving forces. The accuracy of the modified expression is

29% with underestimations found for 88% of all cases. Compared to the original design expression made by De Gids & Phaff (see Figure 4a), this expression overestimated most of the time and had a general accuracy of 29%. The largest overestimation of 95% was found for the case with $\Delta T = 0^{\circ}\text{C}$ and $U = 1\text{m/s}$. This illustrates very well the problem with overestimations at low driving forces mentioned earlier. The design expression developed by Larsen (see Figure 4C) also takes the wind direction into consideration. This expression slightly underestimates and has an accuracy of 23%, but includes a longer calculation time, due to the extra information needed for this expression. Also Larsen has the largest deviations between calculated and measured values in the isothermal cases.

4. Discussion

The comparison between different simple direct calculation methods for single-sided natural ventilation has shown that the use of simple methods is easy but also contains large uncertainties in the results. For increased certainty in the results, more advanced tools, as for example computational fluid dynamics (CFD), airflow network models or zonal models, are needed, and thereby also heavier and more time consuming methods. In order to choose the right calculation method it is important to look at the purpose of the calculation. Table 2 gives an overview of calculation methods depending on the stage of the design process.

Table 2. Design stages for single-sided natural ventilation

	Conceptual design phase	Detailed design phase
Aim	Estimations of needed window areas based on <ul style="list-style-type: none"> - Air flow rates - Cooling demands 	Documentation of sufficient window areas based on <ul style="list-style-type: none"> - Needed air flow rates - Cooling demands Documentation of: <ul style="list-style-type: none"> - Thermal comfort - Atmospheric comfort
Tools/calculations	Simple and fast methods for estimations, eg. De Gids & Phaff, modified De Gids & Phaff, Larsen	Detailed calculations with detailed input, eg. CFD, airflow network models or zonal models
Target group	Architects, engineers, regulators	Engineers

Table 2 shows the need for both simple and detailed calculation methods throughout the design of a building. The details needed decide which level of accuracy the calculation is performed with.

Another parameter that comes into consideration is the purpose of the designed natural ventilation – is it for handling cooling demands (ventilative cooling) or for general comfort ventilation? The modified De Gids & Phaff expression developed for ventilative cooling in FprEN 16798-7 was developed with the purpose of reducing the risk of overestimating air flows in individual cases with different temperature

difference, wind direction and wind velocity. Other design expressions are developed with the aim of an overall accurate prediction of the air flows, not aiming for an underestimation. The analysis in this paper shows that the target for the modified De Gids & Phaff expression is obtained by an average underestimation as illustrated in Figure 4b and Table 1.

5. Conclusion

The comparison of the new modified De Gids & Phaff calculation method for single-sided natural ventilation with earlier design expressions reveals strengths and weaknesses based on the aim of the calculation. The new simplified calculation method showed results generally on the safe side with a deviation between calculated and measured values of 29% and the authors consider the simplified calculation method well suited for the use in standards such as FprEN 16798-7 for the ventilative cooling effects from single-sided natural ventilation. The original De Gids & Phaff design expression has the same accuracy but with a general overestimation. The design expression developed by Larsen was also slightly underestimating the flow and had an accuracy of 23%. This design expression is as the only one, also including the wind direction and thereby also requires slightly more work for the calculations.

Guidelines on when to use which level of details in the calculations were given. Here the main conclusion is to use the simple design methods for the early design where a rough estimate of airflows with a fast calculation is sufficient. Later in the building design more detailed methods as CFD or zonal models are needed for accurate documentation of the building.

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